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N AND Δ RESONANCES -- AN EXPERIMENTAL REVIEW

MASTER

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ABSTRACT

Experimental progress in N and Δ resonances since the Oxford baryon conference is reviewed. The review concentrates on hadronic channels, and on developments of the last one or two years. The topics reviewed include the antiproton lifetime; the Δ^{++} magnetic moment; measurements of πN elastic and charge-exchange scattering in the Δ region, the ηn threshold region, and the high mass region; partial wave analyses of $\pi N \to \pi N$; measurements of two-body inelastic πN scattering; and isobar analyses of $\pi N \to \pi\pi N$.

INTRODUCTION

Knowledge of the non-strange baryon resonances has significantly advanced since the last conference in this series at Oxford in 1976. Most of the progress has been in the determination of properties of baryons whose existence is already established, although a number of new high mass resonance candidates have also been proposed. I will review the results of experiments and analyses performed since the Oxford conference, concentrating on results obtained in the last couple of years. I will also restrict myself primarily to hadronic channels. The electromagnetic interactions of S = 0 baryons are reviewed in talks at this conference by R. Kajikawa, F. Foster, I. Arai, and R. L. Crawford.[0a-0d]

ANTIPROTON LIFETIME

Before discussing the unstable baryons, it is worth noting that since 1977 the lifetime limit of the antiproton has been improved by some 23 orders of magnitude, from 10 nanoseconds to 10 million years. Prior to 1977 a lower limit on the lifetime could only be inferred from the existence of separated antiproton beams. The best present limit from an accelerator was obtained last year in a search for $\bar{p} \to e^-\pi^0$ using antiprotons stored in the Initial Cooling Experiment ring at CERN.[2] A better limit can be inferred from the recent detection of a $\bar{p}/p$ ratio of $(5.2 \pm 1.5) \times 10^{-4}$ in the primary cosmic ray spectrum (for $\bar{p}$ momenta between 5.6 and 12.5 GeV/c).[3] This $\bar{p}/p$ ratio is consistent with production in the interstellar medium, and thus implies a lifetime at least as long as the galactic cosmic ray confinement time.

From a cosmological point of view it is interesting to compare $\tau_{\bar{p}}$ to the age of the universe, $\tau_{universe} \sim 5 \times 10^9$ years. One way to explain the observed matter vs. antimatter imbalance in the universe is to blame it on $\bar{p}$ decay; this requires $\tau_{\bar{p}} < \tau_{universe}$. As the following table shows, this explanation can still not be completely ruled out.

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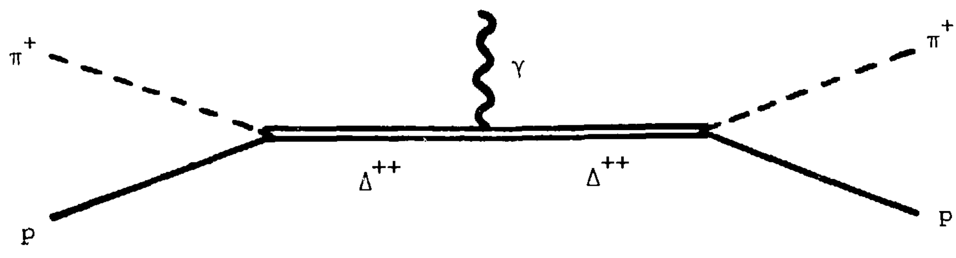
Date	Method	$\tau_{\bar{p},min}/(5 \times 10^9$ yr)
<1977	Existence of separated $\bar{p}$ beams (Cline et al.)[1]	$\sim 10^{-26}$
1977	Search of $\bar{p}$-beam tracks in HBC film (Tata Inst.)[4]	8×10^{-22} (95% CFL)
1979	7000 $\bar{p}$'s stored in ICE ring for 10 days (CERN)[2]	4×10^{-11} x BR ($\bar{p} \to e^-\pi^0$) (90% CFL)
1979	Detection of $\bar{p}$ component in primary cosmic ray spectrum (PSL-NASA)[3]	$\sim 10^{-3}$ (cosmic ray storage time)

Δ^{++} MAGNETIC MOMENT

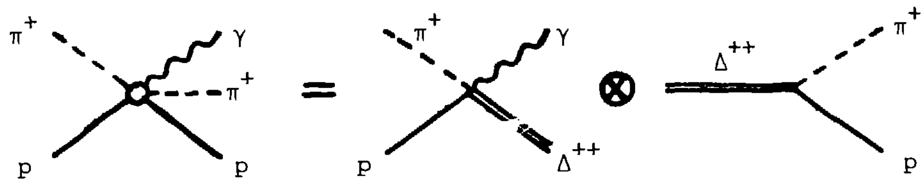
Measurements of $\pi^+p \to \pi^+p\gamma$ in the delta region provide a possible method for determining the magnetic dipole moment of the Δ^{++}. The interest in this quantity comes from the quite unambiguous quark-model prediction that $\mu_{\Delta^{++}} = 2\mu_p = 5.6\ \mu_N$. Many theoretical papers have attacked the problem of extracting $\mu_{\Delta^{++}}$ from data on this reaction. Initial expectations[5] were that $\mu_{\Delta^{++}}$ could be determined from measurements in an appropriately chosen kinematic region in which the dominant reaction mechanism is off-shell radiative Δ decay,



A large resonance enhancement, sensitive to $\mu_{\Delta^{++}}$, is then predicted in the γ-ray spectrum.

Measurements of the γ-ray spectrum at several energies and many production angles have been made at the LBL 184-inch cyclotron by a UCLA group.[6,7] No resonance enhancement was observed in any of the spectra. Furthermore, parameter free predictions for the photon spectra have been obtained by Liou and Nutt[8] who apply Low's theorem directly to the $\pi^+p \to \pi^+p\gamma$ reaction, obtaining the spectra completely in terms of π^+p elastic scattering. The quantitative success of their predictions in fitting the UCLA data are further evidence that off mass-shell and resonance contributions are small.

In spite of this, it is still possible to extract a value of $\mu_{\Delta^{++}}$ from the data using a method proposed by Pascaul and Tarrach.[9] In their method, one concentrates on photon energies corresponding to a on-shell final state Δ. The narrow resonance approximation is then used to factor the amplitude,



and Low's theorem is used to parametrize the first factor in terms of $\mu_{\Delta^{++}}$. The surprising result of this analysis is that the γ-production cross section, considered as a function of $\mu_{\Delta^{++}}$, displays a deep minimum near the SU(6) value. In the vicinity of this minimum the resonance enhancement is quenched, in agreement with the data. Pascaul and Tarrach obtain $\mu_{\Delta^{++}} = (5.7 \pm 2.1)\ \mu_N$, and Nefkens et al.[6] obtain $\mu_{\Delta^{++}} = (5.7 \pm 1.0)\ \mu_N$ on comparison with more extensive data. External radiation in the final state is neglected in this analysis, but it is not expected to have much effect on the location of the minimum. More important are the use of the narrow resonance approximation and the application of Low's theorem to photons with energies as high as 60 to 80 MeV.

MEASUREMENTS OF πN ELASTIC AND CHARGE-EXCHANGE SCATTERING

A series of precise low energy elastic polarization measurements have been made by a Swiss collaboration at the SIN meson factory.[10-13] π^+p polarizations were measured at 8 momenta between 188 and 427 MeV/c, and π^-p polarizations were measured at 408 and 425 MeV/c. Energy independent phase shift analyses were carried out using these data, and although the data often disagreed significantly with the predictions of the earlier analysis of Carter et al.[14], the agreement with the phase shifts was generally good. The precision of the phase shift determinations was greatly improved by the inclusion of the polarization data, and the I = 3/2 D-wave phase shifts were determined with significant precision for the first time.

Measurements of elastic and charge exchange differential cross sections between 300 and 700 MeV/c have been carried out at Los Alamos by a UCLA group. The measurements are very precise, with statistical uncertainties of less than 2% for the elastic DCS and 2-4% for the CEX DCS. These data are discussed in the talk of D. Fitzgerald.[20a]

Elastic cross-section and polarization measurements extending to somewhat higher energies have been made at the Leningrad Institute of Nuclear Physics cyclotron.

Leningrad Cyclotron

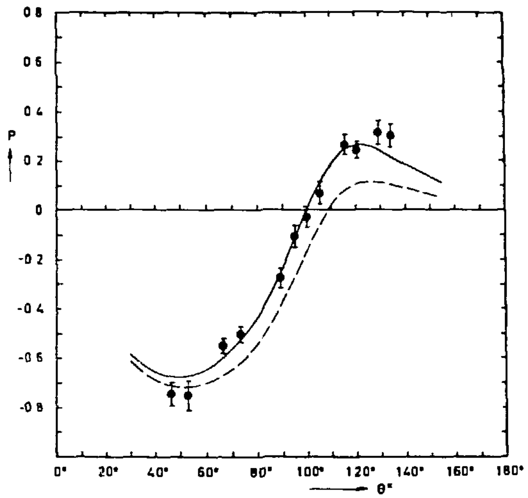
Measurement	Momentum Range (MeV/c)	No. of Momenta
π^+p DCS[15,16]	393-726	12
π^-p DCS[15,16]	404-767	10
π^+p POL[19]	573	1
π^-p POL[17-20]	573-726	6

Some of the polarization measurements were made using an unpolarized target and detectors in which second scattering of the recoil proton in a graphite analyzer was observed. Future plans include the use of these detectors, in combination with a longitudinally polarized target, to measure elastic spin rotation parameters. A phase shift analysis using some of these data[19] indicated that a measurement of the A parameter in π^-p scattering at about 600 MeV/c would be particularly useful in resolving ambiguities that affect the Roper resonance.

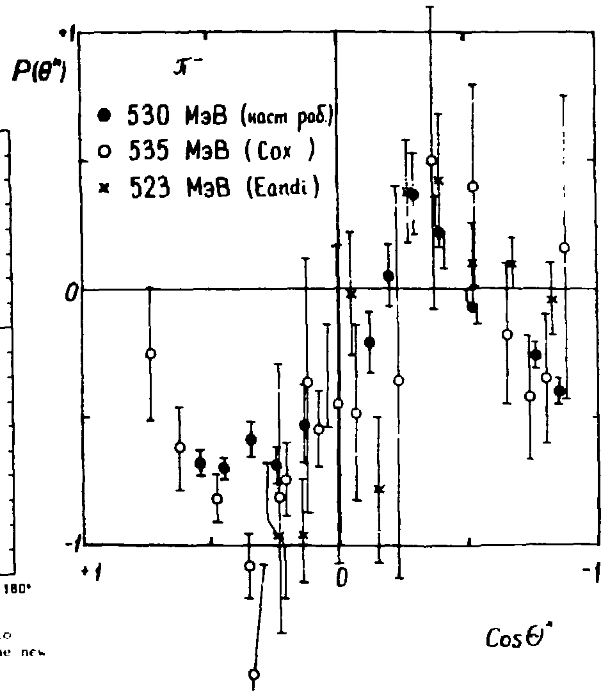
An Imperial College group[21] working at Rutherford Laboratory has made an interesting measurement of π^-p elastic scattering in the neighborhood of the $\pi^-p \rightarrow \eta n$ threshold at 687 MeV/c. The threshold singularity term in the πN elastic S_{11} partial wave amplitude is,

$$\frac{3i}{8\pi}\, q^2_{\pi,th}\, \sigma'_\eta\, e^{2i\alpha}\, q_\eta$$

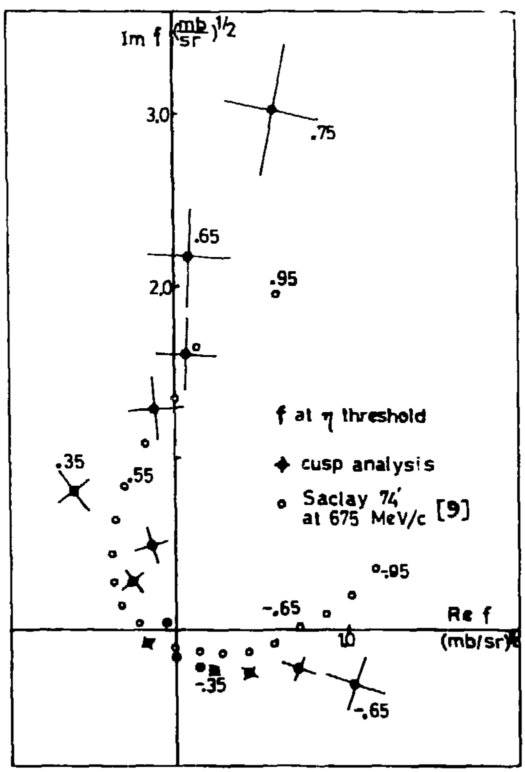
where the energy dependence is contained in q_η = the cm η momentum in $\pi^-p \rightarrow \eta n$, which is proportional to $\sqrt{s - s_{th}}$. The constant coefficients multiplying q_η are $q_{\pi,th}$ = the cm pion momentum at threshold, σ'_η = the derivative of the $\pi^-p \rightarrow \eta n$ cross section with respect to q_η at threshold (= 21.2 ± 1.8 μb/(MeV/c))[22], and α = the phase of the $\pi^-p \rightarrow \eta n$ s-wave amplitude at threshold (= $41^\circ \pm 6^\circ$).[23] The interference between this term and the rest of the non-spin-flip $\pi^-p \rightarrow \pi^-p$ f amplitude produces a characteristic threshold cusp in the energy dependence of the differential cross section at fixed angle. The strength and shape of the cusp depend on the magnitude and phase of f_{th}, and the complete amplitude can be extracted from sufficiently accurate data near the cusp. Sarma et al.[21] have determined f_{th} at 15 angles; their results are shown in Fig. 1 and compared to the partial



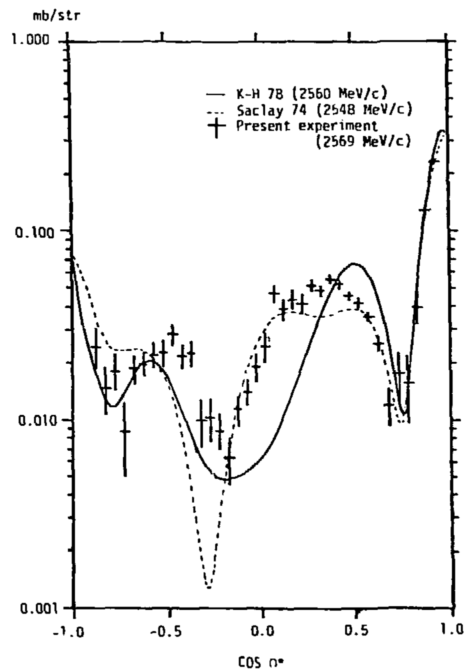
SIN π^-p polarization data at 408 MeV/c compared to predictions of Carter et al. (dashed line) and the new fit of Alder et al. (solid line).



Leningrad π^-p polarization data at 655 MeV/c compared with older data.



π^-p elastic f amplitude from Imperial College measurements of the π^-p elastic differential cross section near the ηn threshold (687 MeV/c).



Kyoto University $\pi^-p \to \pi^0 n$ differential cross section data at 2569 MeV/c.

Fig. 1. Results of some recent measurements of $\pi N \to \pi N$ scattering.

wave analysis of Ayed.[24] The ηn threshold is at 1488 MeV which is very close to the mass of the Roper resonance. The data of Sarma et al. should provide an important constraint for future partial wave analyses in this region.

As a byproduct of measurements of $\pi^+p \to K^+\Sigma^+$ [24a], measurements of π^+p elastic scattering in the backward hemisphere have been made at CERN at 25 momenta in the momentum range 1.3 to 2.5 GeV/c. Preliminary data at 6 momenta are discussed in the talk of M. G. Green.[24b]

A program of π^-p elastic and charge-exchange measurements between 2 and 4 GeV/c has been carried out at KEK. Elastic Measurements were made by a Nagoya-Hiroshima-Osaka-KEK collaboration, and charge-exchange measurements by a Kyoto University group. The charge-exchange data are discussed in the talk of K. Miyake.[29a]

KEK

Measurement	Momentum Range (MeV/c)	No. of Momenta
π^-p DCS[25]	2060-3480	8
π^-p POL[26]	2220-3500	4
CEX DCS[27,28,29a]	1970-2960	6
CEX POL[27,29,29a]	1970-4220	8

The agreement of the cross-section data with the results of previous partial wave analyses[24,30] is generally qualitatively good, although there are discrepancies at some momenta. The worst discrepancies occur for the $\pi^-p \to \pi^0n$ data at 2569 MeV/c where there were no previous data, and where the partial wave analyses also disagree seriously with each other. This is shown in Fig. 1. The agreement of partial wave analyses with the polarization data is generally not even qualitatively good. This is not altogether unexpected because the predicted polarizations were largely unconstrained in this energy range prior to the KEK measurements. These disagreements emphasize the continuing need for more high quality data above 2 GeV/c to clarify the properties of high mass resonances.

A Columbia-ANL-Minnesota group has measured $\pi^{\pm}p$ elastic scattering cross sections at wide angles, $-0.3 < \cos\theta < 0.4$, in narrow momentum steps.[31] $\pi^{+}p$ cross sections were measured from 2.0 to 6.3 GeV/c, and $\pi^{-}p$ cross sections from 2.0 to 9.0 GeV/c, both in 2% momentum steps. When the data are displayed at fixed t as a function of s, pronounced narrow structures (full width ~100 to 200 MeV) are seen in some of the curves. Comparison of the data with statistical models leads to the conclusion that the observed structure is qualitatively consistent with the mechanism of Ericson fluctuations, i.e., multiple overlapping resonances. These data and the KEK data have been included in the latest version of the Karlsruhe-Helsinki analysis[32,32a] which finds many high mass resonance candidates.

Measurements made at CERN of $\pi^{-}p$ elastic differential cross sections at large angles (6-13 GeV/c) and $\pi^{-}p$ total cross sections (2-14 GeV/c) are described in the table of P. Baillon.[32b] These measurements are made with very high statistics and fine momentum resolution, in order to search for narrow resonances. Unlike the ANL measurements,[31] the CERN experiment does not observe narrow structures.

PARTIAL WAVE ANALYSES OF πN ELASTIC AND CHARGE-EXCHANGE SCATTERING

An energy-dependent partial wave analysis in the low energy region (threshold to 470 MeV/c) has been carried out by Zidell et al.[33] The analysis includes contributions from all waves with $L \leq 3$. All waves except P_{11} are assumed to be elastic, and are fit with an energy-dependent parametrization of $\tan\delta$. The P_{11} is allowed to be inelastic, and is fit with a two-channel K-matrix parametrization. Deviations from isospin invariance (in addition to electromagnetic corrections) are allowed for by using different S_{31} and P_{33} waves for $\pi^{+}p$ and $\pi^{-}p$ scattering. The Δ^{++} and Δ^{o} pole positions are determined to be,

$$W^{++} = (1210.70 \pm 0.16 \text{ MeV}) - 1/2\, i(99.21 \pm 0.23 \text{ MeV})$$

$$W^{o} = (1210.3 \pm 0.36 \text{ MeV}) - 1/2\, i\,(108.0 \pm 0.52 \text{ MeV})$$

Note that the real parts are about 20 MeV below the Breit-Wigner mass, and that there is significant isospin violation in the imaginary parts. These features of the pole positions were known previously, but the new analysis obtains errors about three times smaller than previous results. Scattering lengths are determined for the S and P waves[33,34], with different values in the $\pi^{+}p$ and $\pi^{-}p$ channels for S_{31} and P_{33}. A dispersion relation consistency check by the Karlsruhe group[32] indicates that there may be some inconsistencies in the results of Zidell et al. in the $\pi^{-}p$ channel at very low energies.

An energy-independent analysis at 28 momenta below 500 MeV/c has been carried out by Koch and Pietarinen.[35] They retain all waves with $L \leq 3$, allow P_{11} to become inelastic above 360 MeV/c, and allow other waves to become inelastic above 450 MeV/c. The invariant amplitudes are constrained to satisfy fixed-t dispersion relations. Koch and Pietarinen claim that all evidence for violations of isospin invariance (other than electromagnetic corrections) come from the total cross section data, and that the low energy differential cross section and polarization data are not sufficiently accurate to show this effect. They therefore do the main part of their analysis in an isospin invariant approximation, using the isospin invariant forward amplitudes of Höhler et al.[36] as constraints. The accurate total cross section data of Pedroni et al.[37] are then fit, with all waves except P_{33} held fixed, and mass splitting of the Δ^{++} and Δ^{0} is observed. Unlike Zidell et al., this analysis allows for no isospin violation in the S_{31} wave.

The CMU-LBL partial wave analysis[38-40,40a] concentrates on the energy region above the Δ in which high precision data are available over the entire angular range from 0^{o} to 180^{o}. Published results extend from 430 to 2000 MeV/c, and the analysis has now been extended to 2500 MeV/c. Before fitting, the data from various experiments are interpolated and combined ("amalgamated") into coordinated datasets at fixed momenta. Energy independent fits are the performed, using a parameterization that incorporates t- and u-channel analyticity, and many local minima are generated from random starting points scattered over large regions in parameter space. Statistically indistinguishable minima are combined into clusters characterized by a correlated set of partial wave amplitudes. Fits of the invariant amplitudes along 5 crossingsymmetric hyperbolae in the Mandelstam plane are used to select the favored cluster at each energy, and to reduce its size. The resulting data on individual partial wave amplitudes are then fit with a coupled channel resonance-plus-background parametrization in which the effects of overlapping resonances, opening inelastic channels, and centrifugal barriers are included. Resonance masses, widths, and elasticities defined in the conventional way, as well as pole positions and residues, are extracted from these fits. A unique feature of this analysis is the incorporation of realistic error propagation at every stage.

The Karlsruhe-Helsinki analysis[30,32,32a] covers the momentum range from threshold to 10 GeV/c. Energy independent fitting is done with a standard partial wave parametrization including many high partial waves at the higher energies. Like the CMU-LBL analysis, the results of the energy independent fits are subjected to energy dependent analyticity constraints. The invariant amplitudes at fixed t values are required to fit an analytic crossing-symmetric parametrization in s. In addition, the invariant amplitudes at fixed θ are constrained by a dispersion relation parametrization which includes a calculated nearby left-hand cut contribution. The fixed-θ constraints are particularly important above ~3 GeV/c where the fixed-t constraints become confined to forward angles. The fixed-s, fixed-t, and fixed-θ analyses are iterated to obtain a consistent solution. Results extracted from the final partial wave amplitudes include resonance masses, widths, and elasticities, low energy parameters, extrapolated $\pi\pi \rightarrow N\bar{N}$ amplitudes, and zero trajectories for invariant amplitudes. The agreement between the CMU-LBL and Karlsruhe-Helsinki analyses is generally good, where they overlap, although some important differences remain. In particular, the $D_{35}(1930)$ and $F_{17}(1990)$ resonances in the Karlsruhe-Helsinki analysis are rather weak compared to the resonance signals seen by CMU-LBL.

π^+p elastic scattering data between 0.6 and 2.3 GeV/c have been analyzed by Chew[41,41a] using the method of Barrelet[42]-Gersten[43] zeros. Transversity amplitudes at fixed energy are parametrized in terms of polynomials in $w = e^{i\theta}$, with the locations of the transversity-amplitude zeros in the w-plane as free parameters determined by fitting. The earlier version of this analysis[41] did not obtain Breit-Wigner fits to the well-established $S_{31}(1650)$ and $P_{31}(1910)$ resonances. It has also been criticized[32] for having an overall phase that differs appreciably from that of CMU-LBL and Karlsruhe-Helsinki. The more recent version of this analysis[41a] presented at this conference claims 5 S_{31} resonances and 4 P_{31} resonances in the 1700-2200 MeV mass range.

Hendry[44,44a] has carried out a partial wave analysis in the high mass region aimed at determining the properties of the most prominent peripheral high-spin resonances. At each energy the partial wave amplitudes are parameterized as functions of impact parameter, $b = L/k$, using a two-component absorptive model. The parameterization includes a Pomeron component which is a Gaussian in b centered at $b = 0$, and t- and u-channel exchange terms which are Gaussians in b centered at $b = 1$ fm. After fitting the model amplitude in terms of a small number of parameters, the individual partial waves are allowed to vary somewhat to improve the fit to the data. Many candidates for high mass resonances are found.

One of the more interesting results of the CMU-LBL analysis is evidence for mass splitting of the Δ members of the $[70,1^-]$, the S_{31} and D_{33}. As shown in Fig. 2, the observed splitting is consistent with the results of other $\pi N \rightarrow \pi N$ analyses.[24,30,45] Mass determinations from inelastic channels, particularly photoproduction, are included in the large mass ranges given by the Particle Data group[46] which make the S_{31} and D_{33} masses appear to be consistent with degeneracy. However, the $\pi N \rightarrow \pi N$ analyses probably give more accurate results, and the presence of mass splitting should be taken seriously. The importance of this is that these are very degenerate states in a perturbed harmonic oscillator quark model. The degeneracy can not be lifted by an SU(6) symmetric scalar potential, by spin-spin interactions, or by two-body $\underline{L}\cdot\underline{S}$-type spin-orbit interactions. The states can be split by the so-called "three-body spin-orbit interaction" which is really a two-body relativistic spin-orbit interaction contained in the single gluon exchange potential.[46a] A calculation of the splitting including this term by Gromes and Stamatescu[47] finds $M(D_{33}) - M(S_{31}) \approx 55$ MeV. Before concluding that this is really the correct mechanism for D_{33}-S_{31} splitting one should check its effect on the rest of the spectrum, including the effect on mixing angles and on Y*'s. In the bag model spectrum of DeGrand and Jaffe[48,49] there is no reason for these states to be degenerate, and they are split by about 95 MeV, but their masses are much too low, particularly the S_{31} mass which lies at 1390 MeV.

At the next level of the harmonic oscillator spectrum there are 5 $SU(6) \otimes O(3)$ multiplets, the $[56,0^+]^*$, $[56,2^+]$, $[70,0^+]$, $[70,2^+]$, and $[20,1^+]$. The $[20,1^+]$ has an antisymmetric flavor-spin wave

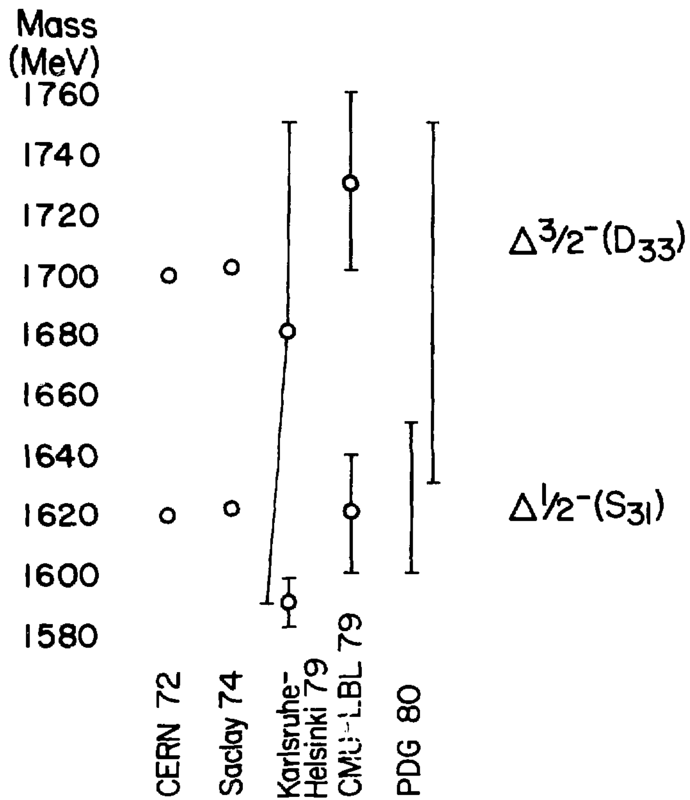


Fig.2. D_{33}-S_{31} mass splitting in the $[70,1^-]$.

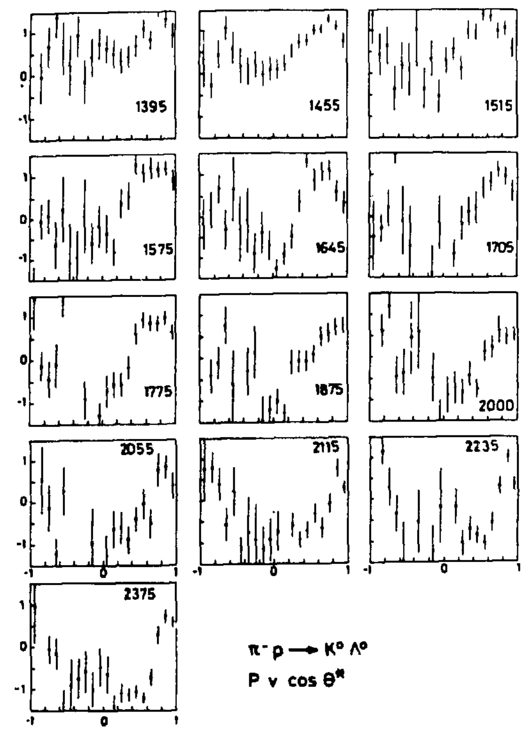


Fig.3. The polarization data of Saxon et al. plotted against cm scattering angle for the different incident beam momenta.

function, and its non-strange members cannot decay to πN via single quark transitions. There is no obvious reason, however, why the 19 non-strange members of the remaining multiplets should not be observed. The CMU-LBL and Karlsruhe-Helsinki analyses confirm the results of previous analyses that in fact only about half of these states couple to πN. No more than 10 states can be assigned to the 19 available slots. The missing states could all be assigned to the $[70,0^+]$ and $[70,2^+]$, and this has contributed to the notion that even 70's and odd 56's are absent from the physical spectrum. (Or nearly absent; there is at least one N*, the $F_{17}(1990)$, that can be rather unambiguously assigned to the $[70,2^+]$.) Recent work of Isgur and Karl[50-52] and Koniuk and Isgur[53,53a] indicates a solution to this problem. Isgur and Karl calculate baryon wave functions and masses in a specific broken-SU(6) model with spin-spin interactions arising from single gluon exchange. At the N = 2 level they find extensive mixing among the SU(6) multiplets, so much mixing that even qualitative assignments of resonances to a single multiplet are in many cases not possible. Koniuk and Isgur calculate meson and radiative decay amplitudes using the wave functions of Isgur and Karl and using simple vertices for meson and photon emission by quarks. Considering the simplicity of the model, and the small number of adjustable parameters involved, the overall agreement with experiment is reasonably good. In particular, the observed decoupling pattern of the N = 2 N's and Δ's is reproduced.

The Karlsruhe-Helsinki and Hendry analyses have found numerous new candidates for high-spin resonances with masses $\gtrsim$2500 MeV. These resonances are important for understanding the behavior of leading Regge trajectories where deviations from the usual linear behavior in M^2 may begin to appear due to centrifugal barrier effects. The agreement between the older Karlsruhe-Helsinki results[30] and Hendry was not particularly good; in no more than 4 cases could the resonance claims of the two analyses above 2500 MeV reasonably be said to coincide -- $I_{111}(2600)$, $K_{113}(2700)$, $I_{313}(2750)$, and $K_{315}(2950)$. This situation appears to have improved in the more recent results.[32,32a]

πN 2-BODY INELASTIC REACTIONS

Extensive measurements of π^-p inelastic reactions were made at Rutherford Laboratory prior to the shutdown of Nimrod. The $\pi^-p \to K^0\Lambda$ polarization data of Saxon et al.[56] are shown in Fig. 3. In addition to the experiments listed below, a $\pi^+p \to K^+\Sigma^+$ experiment was initiated at Rutherford[59] and is now continuing at CERN.[60,24a]

Rutherford

Measurement	Momentum Range (MeV/c)	No. of Momenta
$\pi^- p \to \eta n$ DCS[54]	724-2723	20
$\pi^- p \to \eta n$ POL[55]	1171-2267	12
$\pi^- p \to K^o\Lambda$ DCS[56]	1395-2375	13
$\pi^- p \to K^o\Lambda$ POL[56]	1395-2375	13
$\pi^- p \to K^o\Sigma^o$ DCS[57,58]	1040-2375	19
$\pi^- p \to K^o\Sigma^o$ POL[57,58]	1040-2375	19

Partial wave analysis of 2-body inelastic reactions is very important for understanding the SU(6) composition of baryon resonances. These analyses are reviewed by P. J. Litchfield[24a] at this conference, so I will just make one comment concerning the results of Saxon et al.'s analysis of $\pi^- p \to K^o\Lambda$. The $K^o\Lambda$ channel is particularly clean in that it is pure $I = 1/2$ and it couples only to the quark spin $S = 1/2$ component of N*'s through single quark transitions. There are three N*'s in the $[70,1^-]$ multiplet with masses around 1700 MeV. One of these, the D_{15}, is pure $S = 3/2$, and the other two, the D_{13} and S_{11}, could be mixtures of $S = 1/2$ and $S = 3/2$. However, both non-relativistic quark models based on single-gluon exchange breaking of SU(6) symmetry[50] and the relativistic bag model[49] find that the D_{13} is nearly pure $S = 3/2$, while the S_{11} is a mixture with an appreciable $S = 1/2$ component. It is an important confirmation of these ideas that Saxon et al. find small $K^o\Lambda$ branching ratios of 0.2% for the D_{15} and D_{13}, and find a rather large branching ratio of 8% for the S_{11}. The S_{11} branching ratio agrees quantitatively with the decay calculations of Koniuk and Isgur.[53] One can even obtain the right order of magnitude for the D-wave decays using the small $S = 3/2$ component of the Λ arising from mixing of the ground state and $[70,2^+]$ wave functions.[53b]

ISOBAR MODEL ANALYSES OF $\pi N \to \pi\pi N$

At the time of the Oxford conference the Berkeley-SLAC[61,62] and Saclay[63,64] analyses were in their final stages, and preliminary results from the Imperial College analysis were discussed.[65] Two new analyses have appeared in the interim, and the Imperial college analysis has been completed.

Arndt et al.[66] have analyzed 4000 $\pi^- p \to \pi^+\pi^- n$ bubble-chamber events at 1340, 1360, and 1375 MeV. All isobar production amplitudes with a final-state S-wave or with a final state P-wave arising from a resonant initial state were included: ΔPP11, εPS11, ΔPP33, ΔDS13, ε^nP13, and ΔDS13. A chiral-symmetry background contribution calculated from a phenomenological Lagrangian was also included. Single pion production is found to be dominated by the initial P_{11} wave, and the production of the εN final state in this wave is found to be more important than $\pi\Delta$.

The Imperial College analysis[67] fits 44,000 $\pi^+ p \to \pi^+\pi^0 p$ and $\pi^+ p \to \pi^+\pi^+ n$ events at 9 cm energies between 1439 and 1692 MeV. The final states $\pi\Delta$, ρN, and $\pi N^*(1470)$ were used, and all isobar production amplitudes up to a cutoff value of J which ranged from 3/2 to 7/2 were included. An incoherent OPE background with S-wave I = 2 final state $\pi\pi$ interactions was also included. Clear signals for the S_{31} and D_{33} members of the $[70,1^-]$ were observed, and improved determinations of the ρN couplings were made. A broad $P_{33}(1690)$ is observed, but with the possibility of a second, narrow P_{33} around 1600 MeV. One of the most interesting results of this analysis is the claim that there is a narrow (Γ = 40 MeV) P_{31} state around 1525 MeV. A similar effect was seen in the Saclay analysis[64], but it has never been observed in a 2-body final state. The N = 2 level of the harmonic oscillator spectrum contains 2 P_{31} states in the $[56,2^+]$ and $[70,0^+]$ multiplets, and the well-established $P_{31}(1910)$ is generally thought to be one of these. The low mass state observed in $\pi\pi N$ may be the other, but in most models the ~400 MeV mass splitting will be hard to accommodate. For example, Isgur and Karl[51] find wave functions for these states that are roughly equal mixtures of $[56,2^+]$ and $[70,0^+]$ and masses of 1925 and 1875 MeV. One should also note that the energy bins near this resonance in the IC analysis are at 1495, 1526, and 1550 MeV so that the entire resonance signal is coming from essentially a single energy.

Novoseller[68,69] investigated the effect of including high partial waves due to OPE in a fit using identical data and a parameterization for the low partial waves similar to that used in the Berkeley-SLAC energy-independent analysis.[70] Data on $\pi^- p \to \pi^-\pi^0 p$, $\pi^- p \to \pi^-\pi^+ n$, and $\pi^+ p \to \pi^+\pi^0 p$ in the range 1630 to 1990 MeV were used. It was found that above 1800 MeV the inclusion of OPE improves the fit and helps to eliminate the phase ambiguity. Another study of the importance of OPE has been made by Aaron et al.[71] who also found that it can give important corrections to the angular dependence.

The neglect of subenergy dependence in existing isobar models is an approximation which in principal violates unitarity. Aitchison and Brehm[72] have studied this problem, and derived an isobar expansion that is consistent with unitarity and subenergy analyticity. Estimates of the unitarity corrections indicate that they may not be significant for existing isobar fits, but that they could become important with improved experimental data.[73]

In addition to the above studies of resonance formation in $\pi N \to \pi\pi N$ there have been many studies at high energy of non-strange baryons produced in $\pi N \to \pi(\pi N)$, $\pi N \to \pi(\pi\pi N)$, and other reactions. It is difficult to draw firm conclusions about most resonance properties from these experiments because each prominent bump observed in production is generally a coherent superposition of several resonances plus background. There is the possibility, however, that there exist resonances which are not easily seen in formation, but which are observable in production. This possibility has been investigated recently by Fukunaga et al.[74] who claim evidence for three new N*'s at 1344, 1451, and 1639 MeV. If these states are distinct resonances not seen in formation they may be multiquark baryons. For details see the talks of A. Yokosawa[74a], J. J. de Swart[74b], and others at this conference.

REFERENCES

0a. R. Kajikawa, talk given at Baryon 1980, published in these proceedings.
0b. F. Foster, ibid.
0c. I. Arai, ibid.
0d. R. L. Crawford, ibid.
1. D. Cline et al., Phys. Lett. 66B, 429 (1977).
2. M. Bell et al., Phys. Lett. 86B, 215 (1979).
3. R. L. Golden et al., Phys. Rev. Lett. 43, 1196 (1979).
4. S. N. Ganguli et al., Phys. Lett. 74B, 130 (1978).
5. L. A. Kondratyuk and L. A. Ponomarev, Sov. J. Nucl. Phys. 7, 82 (1968).
6. B. M. K. Nefkens et al., Phys. Rev. D 18, 3911 (1978).
7. D. E. A. Smith et al., Phys. Rev. D 21, 1715 (1980).
8. M. K. Liou and W. T. Nutt, Phys. Rev. D 16, 2176 (1977).
9. P. Pascual and R. Tarrach, Nucl. Phys. B134, 133 (1978).
10. J. C. Alder et al., Lettere al Nuovo Cimento 23, 381 (1978).
11. L. Dubal et al., Helv. Physica Acta 50, 815 (1977).
12. C. Amsler et al., Lettere al Nuovo Cimento 15, 209 (1976).
13. C. Amsler et al., Phys. Lett. 57B, 289 (1975).
14. J. R. Carter et al., Nucl. Phys. B58, 378 (1973).
15. V. A. Gordeev et al., Sov. J. Nucl. Phys. 29, 339 (1979).
16. V. A. Gordeev et al., Sov. J. Nucl. Phys. 24, 599 (1976).
17. V. S. Bekrenev et al., LINP-542, Leningrad, 1979.
18. V. S. Bekrenev et al., LINP-466, Leningrad, 1979.
19. V. S. Bekrenev et al., Sov. J. Nucl. Phys. 24, 45 (1976).
20. V. S. Bekrenev et al., Instruments and Experimental Techniques 17, 680 (1974).
20a. D. Fitzgerald, talk given at Baryon 1980, published in these proceedings.
21. H. N. K. Sarma et al., Nucl. Phys. B161, 1 (1979).
22. D. M. Binnie et al., Phys. Rev. D 8, 2789 (1973).
23. R. Bhandari and Y.-A. Chao, Phys. Rev. D 15, 192 (1977).

24. R. Ayed, University of Paris-Sud Thesis, Report No. CEA-N-1921, 1976.
24a. P. J. Litchfield, talk given at Baryon 1980, published in these proceedings.
24b. M. G. Green, ibid.
25. S. Terada et al., HUPD-8004, Hiroshima, 1980.
26. M. Fukushima et al., Nucl. Phys. B167, 307 (1980).
27. K. Miyake, private communication, 1979.
28. Y. Suzuki, Kyoto University thesis, 1979.
29. M. Minowa, Kyoto University thesis, 1979.
29a. K. Miyake, talk given at Baryon 1980, published in these proceedings.
30. G. Höhler et al., Handbook of Pion-Nucleon Scattering (Fachinformationszentrum Energie, Physik, Mathematik, Karlsruhe, 1979), Physik Daten Vol. 12-1.
31. K. A. Jenkins et al., Phys. Rev. D 21, 2445 (1980).
32. R. Koch, TKP 80/12, Karlsruhe, 1980.
32a. R. Koch, talk givn at Baryon 1980, published in these proceedings.
32b. P. Baillon, ibid.
33. V. S. Zidell et al., Phys. Rev. D 21, 1255 (1980).
34. V. S. Zidell et al., Phys. Rev. D 21, 1289 (1980).
35. R. Koch and E. Pietarinen, Nucl. Phys. A336, 331 (1980).
36. G. Höhler et al., KFK-report 2457, Karlsruhe, 1977.
37. E. Pedroni et al., Nucl. Phys. A300, 321 (1978).
38. R. L. Kelly and R. E. Cutkosky, Phys. Rev. D 20, 2782 (1979).
39. R. E. Cutkosky, et al., Phys. Rev. D20, 2804 (1979).
40. R. E. Cutkosky et al., Phys. Rev. D20, 2839 (1979).
40a. R. Cutkosky, talk given at Baryon 1980, published in these proceedings.
41. D. M. Chew, LBL-5306, Berkeley, 1979.
41a. D. M. Chew, talk given at Baryon 1980, published in these proceedings.
42. E. Barrelet, Nuovo Cimento 81, 331 (1972).
43. A. Gersten, Nucl. Phys. B12, 537 (1969).
44. A. Hendry, Phys. Rev. Lett. 41, 222 (1978).
44a. A. Hendry, talk given at Baryon 1980, published in these proceedings.
45. S. Almehed and C. Lovelace, Nucl. Phys. B40, 157 (1972).
46. Particle Data Group, Rev. Mod. Phys. 52, No. 2, Part II (1980).
46a. L. J. Reinders, talk given at Baryon 1980, published in these proceedings.
47. D. Gromes and I. O. Stamatescu, Z. Physik C 3, 43 (1979).
48. T. A. DeGrand and R. L. Jaffe, Ann. Phys. (NY) 100, 425 (1976).
49. T. A. DeGrand, Ann. Phys. (NY) 101, 496 (1976).
50. N. Isgur and G. Karl, Phys. Rev. D 18, 4187 (1978).
51. N. Isgur and G. Karl, Phys. Rev. D 19, 2653 (1979).
52. N. Isgur and G. Karl, Phys. Rev. D 20, 1191 (1979).
53. R. Koniuk and N. Isgur, Phys. Rev. D 21, 1868 (1980).
53a. R. Koniuk, talk given at Baryon 1980, published in these proceedings.
53b. N. Isgur, private communication, 1980.

54. R. M. Brown et al., Nucl. Phys. B153, 89 (1979).
55. R. D. Baker et al., Nucl. Phys. B156, 93 (1979).
56. D. H. Saxon et al., Nucl. Phys. B162, 522 (1980).
57. J. C. Hart et al., RL-79-068, Rutherford, 1979.
58. R. D. Baker et al., Nucl. Phys. B145, 402 (1978).
59. Rutherford Laboratory experiment RHEL-193, P. J. Litchfield spokesman, approved 1977.
60. CERN experiment CERN-S-160, P. J. Litchfield spokesman, approved 1977.
61. R. S. Longacre et al., Phys. Lett. 55B, 415 (1975).
62. R. S. Longacre et al., Phys. Rev. D 17, 1795 (1978).
63. J. Dolbeau et al., Nucl. Phys. B108, 365 (1976).
64. R. S. Longacre and J. Dolbeau, Nucl. Phys. B122, 493.
65. K. W. J. Barnham, in Proc. of the Topical Conf. on Baryon Resonances, R. T. Ross and D. H. Saxon, eds. (Oxford Univ. Press, London, 1976), p. 109.
66. R. A. Arndt et al., Phys. Rev. D 20, 651 (1979).
67. K. W. J. Barnham et al., IC/HENP/78/3, Imperial College, 1979.
68. D. E. Novoseller, Nucl. Phys. B137, 445 (1978).
69. D. E. Novoseller, Nucl. Phys. B137, 509 (1978).
70. D. J. Herndon et al., Phys. Rev. D 11, 3183 (1975).
71. R. Aaron et al., Phys. Rev. D 16, 50 (1977).
72. I. J. R. Aitchison and J. J. Brehm, Phys. Rev. D 20, 1119 (1979).
73. I. J. R. Aitchison and J. J. Brehm, Phys. Rev. D 20, 1131 (1979).
74. C. Fukunaga et al., TMUP-HEP-8005/Exp., Tokyo, 1980.
74a. A. Yokosawa, talk given at Baryon 1980, published in these proceedings.
74b. J. J. de Swart, ibid.